**Computers and Concrete**, *Vol. 14, No. 2 (2014) 175-191*
DOI: http://dx.doi.org/10.12989/cac.2014.14.2.175 

# Mechanical properties and durability of self consolidating cementitious materials incorporating nano silica and silica fume

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(*Received January 23, 2013, Revised June 5, 2014, Accepted June 12, 2014*)

**Abstract.** In recent years, the emergence of nanotechnology and nanomaterial has created hopes to improve various properties of concrete. Nano silica as one of these materials has been introduced as a cement replacement material for concrete mixture in construction applications. It can modify the properties of concrete, due to high pozzolanic reactions and also making a denser microstructure. On the other hand, it is well recognized that the use of mineral admixtures such as silica fume affects the mechanical properties and durability of cementitious materials. In addition, the superior performance of self-consolidating concrete (SCC) and self-consolidating mortars (SCM) over conventional concrete is generally related to their ingredients. This study investigates the effect of nano silica and silica fume on the compressive strength and chloride permeability of self-consolidating mortars. Tests include compressive strength, rapid chloride permeability test, water permeability, capillary water absorption, and surface electrical resistance, which carried out on twenty mortar mixtures containing zero to 6 percent of nano silica and silica fume. Results show that SCMs incorporating nano silica had higher compressive strength at various ages. In addition, results show that nano silica has enhanced the durability SCMs and reduced the chloride permeability.

**Keywords:** nano silica; silica fume; compressive strength; chloride durability, self-consolidating mortars

## 1. Introduction

Up to now, researches performed over the years have been largely aimed at achieving high mechanical performance with cement replacement materials in micro size (Ramezanianpour, Ghiasvand *et al*. 2009; Ramzanianpour, Mahdikhani *et al*. 2009; Ramezanianpour, Pilvar *et al*. 2011). Recently, nanotechnology has attracted considerable scientific interest due to the new potential uses of particles in nanometer scale. A nanometer (nm) is one billionth of a meter. The devices and materials dealt with in nanotechnology are typically in a size range of 0.1 nm to 100 nm. Nanotechnology refers to the science and technology of developing materials at the atomic and molecular level and generating techniques in order to measure and utilize their unique and special mechanical and chemical features. (Antonovič, Pundiene *et al*. 2010; Sanchez and Sobolev 2010; Shah 2010; Jayapalan, Lee *et al*. 2013)

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

Due to the high specific surface area, nanoparticles constitute a highly reactive material. (Khanzadi, Tadayon *et al*. 2010; Yang, Liu *et al*. 2010) Therefore, when nanoparticles are incorporated into cementitious materials, depending on the size of solid particles, new materials with different characteristics from conventional materials were obtained. For instance, Titania nanoparticles leads to the making of self-cleaning properties in the concrete (Chen, Kou *et al*. 2011; Nazari and Riahi 2011; Ramachandran, Vishwakarma *et al*. 2011; Folli, Pade *et al*. 2012) and carbon nanotubes present outstanding mechanical properties such as elastic modulus, ultimate strength and ultimate strain (Melo, Calixto *et al*. 2011; Morsy, Alsayed *et al*. 2011; Collins, Lambert *et al*. 2012; Metaxa, Seo *et al*. 2012). Silica nanoparticles, due to their high pozzolanic reactions and also making a denser microstructure, can modify the properties of concrete.

Several authors have investigated the effect of nano silica in cementitious materials. Generally, The results show that nano silica accelerate the chemical reactions during initial hydration (Ltifi, Guefrech *et al*. 2011; Singh, Bhattacharyya *et al*. 2012; Zhang, Islam *et al*. 2012). Qing *et al*. (Qing, Zenan *et al*. 2007) studied the effect of nano silica on the properties of cement pastes where they conducted several tests such as compressive strength and setting time tests. They indicated that the influence of nano silica and silica fume is different since nano silica makes cement pastes thicker and also accelerates the hydration process. In addition, they showed that bond strengths of paste–aggregate interface incorporating NS are higher than those of control sample and than those incorporating SF. By increasing the NS content, the rate of bond strength increase is more than that of their compressive strength increase.

Similarly, Zhang, *et al*. (Zhang and Islam 2012) studied the effect of nano silica on cement mortars and concretes and reached to the same conclusions (Rheology improvement, increase in compressive strength, No free water, decrease in setting time, porosity and permeability) as obtained earlier by previous authors.

The results of Maghsoudi, *et al*. study (Maghsoudi and Dahooei 2009) showed that the engineering properties of SCC mixtures could not be improved by adding only nano silica. However, a satisfactory behavior can be achieved using silica fume in the SCC mixtures. However, by adding both silica fume and nano silica to the SCC mixtures, the best effect on the engineering properties was reported while comparing to the control mixtures.

Nili, *et al*. (Nili, Ehsani *et al*. 2010) show that mechanical properties and durability of concretes depend on the microstructure of the hardened cement paste. In addition, they concluded that adding 6% silica fume and 1.5% nano silica as partial replacements of cement, improved compressive strength and electrical resistance of concrete and also diminished capillary absorption of the concrete specimens seriously.

According to Jalal, *et al*. (Jalal, Mansouri *et al*. 2012) by the addition of silica fume and nanoparticles, the chloride ion percentage decreased with depth. In addition, compressive strengths improved rather significantly in the mixtures containing silica fume and nanoparticles which may be due to accelerated C–S–H gel formation as a result of increased crystalline $Ca(OH)_2$ amount at the early ages.

In the literature, a number of reports on the effects of nano silica and silica fume additions on the durability of SCC are available and no report on SCM has been reported yet. In this study, the influence of the nano silica and silica fume on the SCM was investigated with respect to the properties of concrete in the hardened state (mechanical properties and durability). Additionally, the densification of microstructure of hardened concrete was analyzed by SEM and EDS techniques.

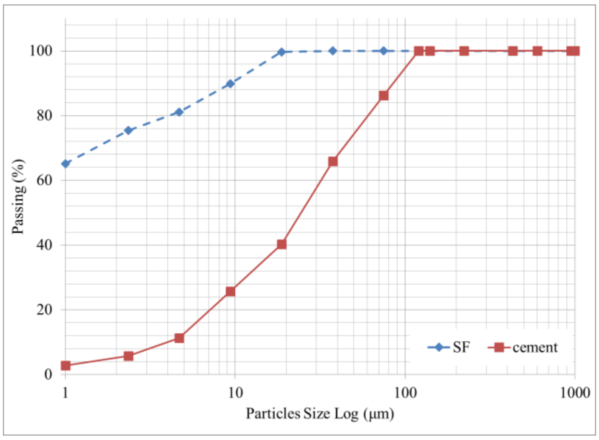



Fig. 1 Sand size distribution

## 2. Materials and mixing procedures

### *2.1Materials*

### *2.1.1. Cement*

Commercial ASTM C 150 (ASTM-C150 2012) type II Ordinary Portland Cement (OPC) was used in all the mortar mixtures. The C3S, C2S, C3A and C4AF contents of the cement by Bogue calculations were 48.68%, 20.33%, 2.82% and 11.99%, respectively. The Physical properties and chemical composition of cement are given in Table1.

### *2.1.2 Aggregates*

Well-graded silica sand was used as fine aggregate. The specific gravity, water absorption and maximum size of the fine aggregates are typically 2.6 and 0.6% and 5 mm, respectively. The grading of the fine aggregate is presented in Fig. 1.

### *2.1.3 Silica fume*

Silica fume is a fine-grain, thin and very high surface area silica. Accordingly, the silica fume used was of powder form with 95% SiO2, 2.35 specific gravity, a particle size of 0.1 µm, and 20 m2/g Blaine fineness. The physical properties and typical chemical analysis of silica fume are shown in Table 1. The particle size distribution (PSD) of cement and silica fume is shown in Fig. 2.

### *2.1.4 Nano silica*

The colloidal nano silica solution used contained 50 wt% of solid material with 2.86 solid specific gravity. Moreover, for determining the exact size of colloidal solutions, particles which was uniformly dispersed in water, Zetasizer system was used. The results of size distribution -measured by the Malvern Zetasizer device- showed that 89.7% of nano silica solution particles had diameter less than 141 nm. (Fig. 3) In addition, the XRF technique shows that the solution contains more than 99% SiO2.

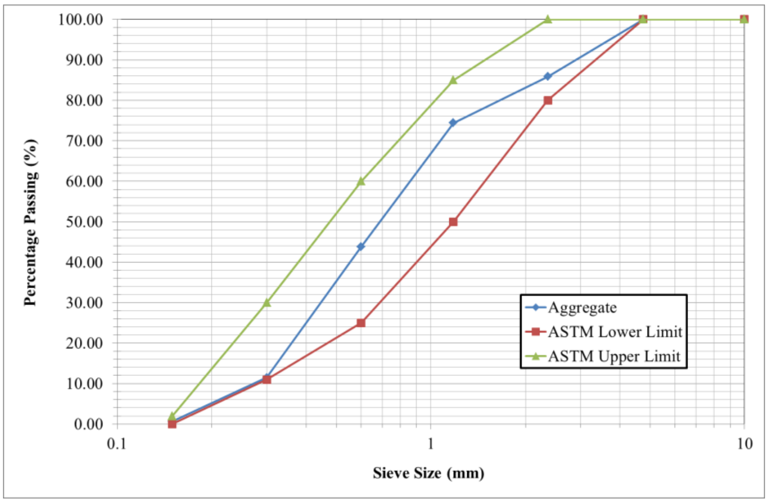



Fig. 2 Particle size distributions for cement and silica fume

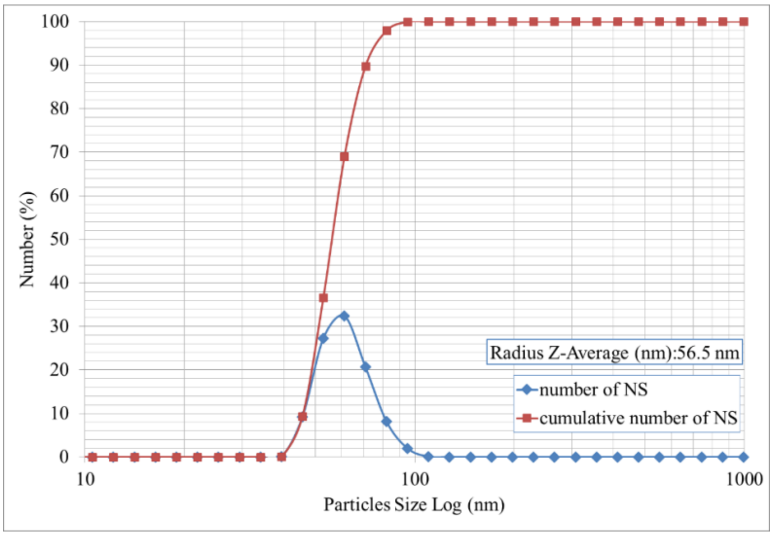



Fig. 3 Nanosilica particle size distribution

Table 1 Chemical and physical properties of cement and silica fume

| Items | Chemical composition (%) | |
|---|---|---|
| | Cement | Silica fume |
| $SiO_2$ | 21.38 | 93.6 |
| $Al_2O_3$ | 4.65 | 1.3 |
| $Fe_2O_3$ | 3.51 | 0.9 |
| CaO | 63.06 | 0.5 |
| MgO | 3.2 | 1 |
| $SO_3$ | 1.8 | 0.1 |
| | Physical properties | |
| Avg. particle size | 10 μm | 0.1μm |
| SSA($m^2$/g) | 0.33 | 20 |

### *2.1.5 Water and water reducer*

Potable water was used for casting and curing of all mortar specimens. A high range water reducing admixture (HRWRA) based on chains of modified polycarboxylic ether was used to achieve the desired workability. It had a specific gravity of 1.1.

### *2.2 Mixing procedures*

Twenty mix proportions of mortars are presented in Table 2. In preparation of SCMs, the mentioned materials for each of the mixtures were mixed in a Hamilton Beach model mixer 63221. Eighty percent of the water and the whole of silica fume and some superplasticizer used to make suitable sludge. Then by adding cement and nano silica, they were placed in the bowl of the mixer and mixed for 30 s at a slow speed (14.66 ± 0.52 rad/s). The entire quantity of aggregate was then added slowly over a 30 s period, while continuing mixing at slow speed. The mixer was stopped and the speed changed to medium (29.84 ± 1.05 rad/s), and ran for 30 s more. The mixer was stopped and the mortar was left to stand for 90 s. During the first 15 s of this interval, any mortar that may have collected on the sides of the bowl was quickly scraped down into the batch.

For the remainder of this interval, the bowl was covered with the lid. Finally, the remaining mixing water containing the superplasticizer was added after which the mixer was restarted and run at medium speed (29.84 ± 1.05 rad/s) for another 2 min.

The dosage of superplasticizer was varied based on Visual Stability Index (VSI). According to ASTM C 1611 (ASTM-C1611 2010), the Visual Stability Index (VSI) procedure assigns a numerical rating of 0 to 3, in increments of one, to the texture and homogeneity of the fresh mixture based on observations made for mixtures (Table 3). In this study, all SCM mixtures were stable in terms of their VSI values which supports the fact of no segregation was observed and slight bleeding was observed as a sheen on the mortar mass. It should be noted that this test result may be misleading, although it provides valuable information on the stability. In addition, the S-shaped test was also taken to visually evaluate the stability of the mixtures.

After casting, all specimens were covered with a wet towel for 24 hours at 22 ± 2℃ before removing from the molds. Immediately after demolding, they cured in accordance with ASTM C-192 (ASTM-C192 2002), in a moist room.

## 3. Test methods

### *3.1 Compressive strength*

Compressive strength tests were conducted on 50 mm cubes, according to ASTM C109 (ASTM-C109 2012) to assess the strength development of mortars at the age of 3, 7, 14 and 28 days cured at 22±2 ℃. The results obtained are reported as an average of at least three samples.

### *3.2 Rapid chloride permeability test (RCPT)*

The Rapid Chloride Permeability Test (RCPT) has become a standard concrete durability measurement of both the AASHTO (AASHTO T277 1989) and the ASTM (ASTM-C1202 2012). In this test, two mortar cylinders with 100 mm diameter and 50 mm lengths were cast for each mixture. The specimens were conditioned in a desiccator attached to a vacuum pump according to


Fig. 4 The RCPT test set-up and apparatus used

Table 2 Mix proportions of mortars

| NO. | Mixture Code | W/C | SF (%) | NS (%) | Cement (kg/m3) | SF (kg/m3) | NS (kg/m3) | HRWRA (%) | Water (kg/m3) | Aggregate (kg/m3) |
|---|---|---|---|---|---|---|---|---|---|---|
| M1 | W40.S0.N0 | 0.40 | 0 | 0 | 650 | 0 | 0 | 0.80 | 260 | 1490 |
| M2 | W40.S2.N0 | 0.40 | 2 | 0 | 637 | 13 | 0 | 0.85 | 260 | 1490 |
| M3 | W40.S4.N0 | 0.40 | 4 | 0 | 624 | 26 | 0 | 0.95 | 260 | 1490 |
| M4 | W40.S6.N0 | 0.40 | 6 | 0 | 611 | 39 | 0 | 1.05 | 260 | 1490 |
| M5 | W40.S0.N2 | 0.40 | 0 | 2 | 637 | 0 | 13 | 1.20 | 260 | 1490 |
| M6 | W40.S2.N2 | 0.40 | 2 | 2 | 624 | 13 | 13 | 1.25 | 260 | 1490 |
| M7 | W40.S4.N2 | 0.40 | 4 | 2 | 611 | 26 | 13 | 1.40 | 260 | 1490 |
| M8 | W40.S0.N4 | 0.40 | 0 | 4 | 624 | 0 | 26 | 1.70 | 260 | 1490 |
| M9 | W40.S2.N4 | 0.40 | 2 | 4 | 611 | 13 | 26 | 1.95 | 260 | 1490 |
| M10 | W40.S0.N6 | 0.40 | 0 | 6 | 611 | 0 | 39 | 2.45 | 260 | 1490 |
| M11 | W50.S0.N0 | 0.50 | 0 | 0 | 650 | 0 | 0 | 0.45 | 325 | 1425 |
| M12 | W50.S2.N0 | 0.50 | 2 | 0 | 637 | 13 | 0 | 0.50 | 325 | 1425 |
| M13 | W50.S4.N0 | 0.50 | 4 | 0 | 624 | 26 | 0 | 0.60 | 325 | 1425 |
| M14 | W50.S6.N0 | 0.50 | 6 | 0 | 611 | 39 | 0 | 0.60 | 325 | 1425 |
| M15 | W50.S0.N2 | 0.50 | 0 | 2 | 637 | 0 | 13 | 0.70 | 325 | 1425 |
| M16 | W50.S2.N2 | 0.50 | 2 | 2 | 624 | 13 | 13 | 0.75 | 325 | 1425 |
| M17 | W50.S4.N2 | 0.50 | 4 | 2 | 611 | 26 | 13 | 0.85 | 325 | 1425 |
| M18 | W50.S0.N4 | 0.50 | 0 | 4 | 624 | 0 | 26 | 0.85 | 325 | 1425 |
| M19 | W50.S2.N4 | 0.50 | 2 | 4 | 611 | 13 | 26 | 0.95 | 325 | 1425 |
| M20 | W50.S0.N6 | 0.50 | 0 | 6 | 611 | 0 | 39 | 1.05 | 325 | 1425 |

Table 3 Visual Stability Index Values

| VSI Value | Criteria |
|---|---|
| 0 = Highly Stable | No evidence of segregation or bleeding. |
| 1 = Stable | No evidence of segregation and slight bleeding observed as a sheen on the concrete mass. |
| 2 = Unstable | A slight mortar halo ≤ 0.5 in. (≤ 10 mm) and/or aggregate pile in the center of the concrete mass. |
| 3 = Highly Unstable | Clearly segregating by evidence of a large mortar halo > 0.5 in. (> 10 mm) and/or a large aggregate pile in the center of the concrete mass. |

ASTM (ASTM-C1202 2012). After conditioning, RCPT was begun using the apparatus shown in Fig. 4. Initially the test cell contains 3.0% NaCl on one side and 0.3 N NaOH on the other. Then, a 60 volt potential is applied across a saturated mortar sample, and the total charge passed through in six hours is measured in coulombs. The current was measured in coulombs for six hours. The more charge detected is indicative of a specimen of high permeability.

### 3.3 Water permeability

The water permeability test, which is used to evaluate the permeability of cementitious materials, is specified by BS EN-12390-8:2000 (EN-12390-8 2000). In this test, 150 mm mortar cubes, after 3, 7, 14 and 28 days of water curing, were dried under laboratory conditions for 6 h. Water was applied to one face of the specimen under a pressure of 0.5 MPa. This pressure was maintained constant for a period of 72 h. After the completion of the test, the specimens were taken out and split open into two halves. The water penetration profile on the specimen surface was then marked and the average depth of water penetration in two specimens was recorded and considered as an indicator of the water penetration.

### 3.4 Capillary water absorption

Capillary water absorption is a term used to describe water ingress into pores of unsaturated mortar due to capillary suction. This test was measured on three 100 mm mortar cubic specimens for each mixture, which were dried in a 50°C oven. After mass stabilization (approximately 3 days), they cool to ambient temperature. Afterwards, the specimens were coated with the epoxy resin on their lateral surfaces only, in order to ensure uniaxial water absorption. The specimen was rested on rods to allow free access of water to the surface and the tap water level was kept no more than 5 mm above the base of the specimen. The masses of the specimens were measured after 0, 3, 6, 24 and 72 h of absorption. The volume of water absorbed was calculated by dividing the mass gained by the nominal surface area of the specimen and by the density of water. These values were plotted against the square root of time. The slope of the best fit line, according to BS EN-480-5:1997 (EN-480-5 1997) was defined as the sorptivity coefficient and may be modeled as:

$$\frac{Q}{A} = c + s\sqrt{t} \quad (1)$$

where Q is the weight of water adsorbed (kg); A is the cross section of the specimen that was in contact with water ($m^2$); $t$ is the time (hours); C is the constant coefficient; and S is the sorptivity coefficient of the specimen ($kg/m^2/hr^{1/2}$).

### 3.5 Surface electrical resistivity

Electrical resistivity is another parameter that contributes to durability assessment. When pores are saturated, depending on the pore structure, electric current flows more easily through the specimen. Therefore, when the current is imposed during the test it is possible to evaluate resistivity in saturated conditions to compare different types of mortar. In addition, this convenient technique measures the in-place surface electrical resistivity of specimen non- destructively. Four equi-spaced electrodes, placed on the surface of the specimen in a linear array were used in

Wenner probe. The electrical resistivity test was carried out on 150 mm mortar cubic specimens, by 40 mm spacing probe array. The test specimens were tested non-destructively at 3, 7, 14 and 28 days. For each mixture, three test specimens were cast. The specimens were removed from the wet chamber immediately before the test at each age and then returned to the chamber immediately after the test.

## 4. Results and discussions

### *4.1 Compressive strength*

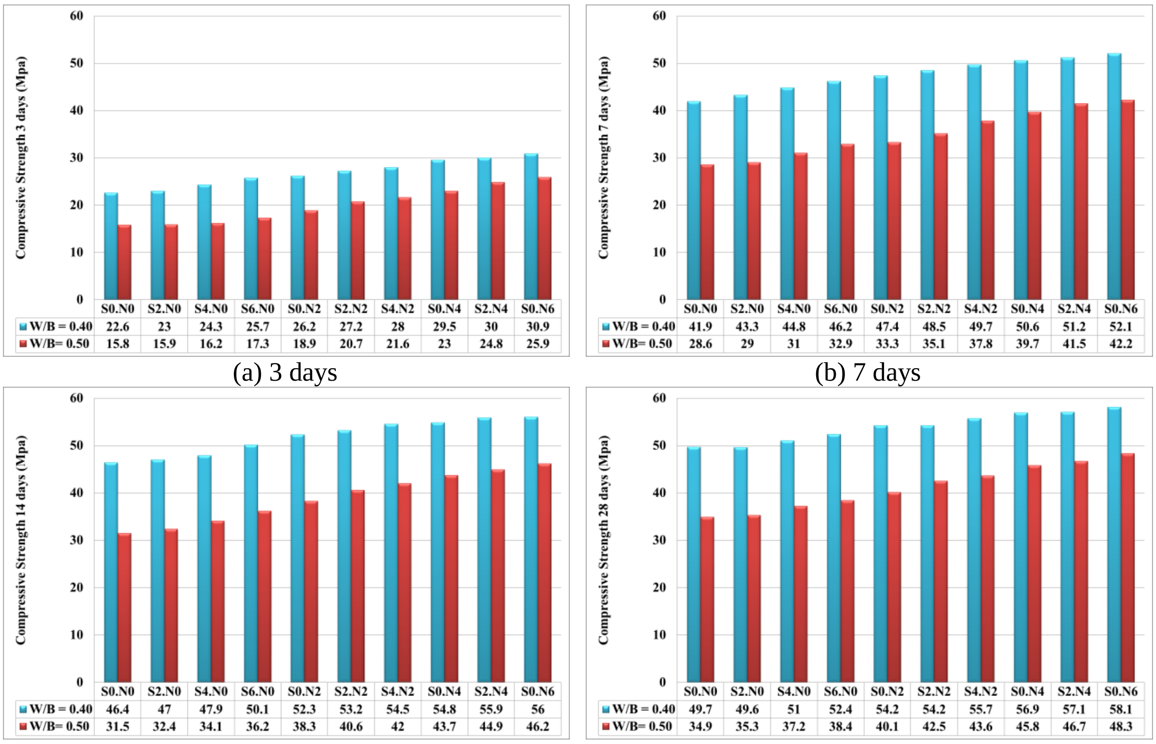
The average compressive strengths of the mortars are presented in Figs. 5(a) to 5(d). The gain in compressive strength continued to occur until the age of 28 days where the highest strength was achieved for all specimens due to greater hydration of cementing materials. However, the largest strength development happened between 3 and 7 days. The compressive strength at the age of 28 days was in the range of 34.9 to 58.1 MPa for different specimens. The highest value of compressive strength was achieved for W40.S0.N6 at age of 28 days, which contained 6% nano silica at the W/B ratio of 0.40. Conversely, the lowest level of compressive strength at age of 3 days was obtained for W50.S0.N0, which was produced with a W/B ratio of 0.50 and without any nano silica or silica fume. Generally, the compressive strength of the specimens increased significantly with lower W/B ratio. In addition, the nano silica and silica fume significantly increased the compressive strength of mortars at the various ages. In addition, the improvement of compressive strength is mostly due to the pozzolanic activity of silica. In the presence of water, the silica actively reacts with $Ca(OH)_2$ liberated during cement hydration (pozzolanic reaction) and produces additional calcium silicate hydrate (CSH), as shown in Eqs. (2) and (3).

$$\text{Hydration reaction: C2S or C3S} + H_2O \rightarrow \text{primary CSH} + Ca(OH)_2 \tag{2}$$

$$\text{Pozzolanic reaction: } Ca(OH)_2 + (SiO_2) + H_2O \rightarrow \text{secondary CSH} \tag{3}$$

The additional CSH increases the compressive strength of specimens since it is a major strength-contributing compound. Also, the additional CSH reduces the porosity of SCMs by filling the capillary pores, and thus improves the microstructure of SCMs in bulk paste matrix and transition zone leading to increased compressive strength. In addition, the results show that with a smaller particle size, the silica can better fill the micro-voids of specimens. As can be seen in results, with the same content of pozzolanic materials, NS samples had a higher compressive strength than SF samples, even at early ages. Therefore, it can be concluded, nanoparticles due to high specific areas are more effective in pozzolanic reaction than silica fume. These findings are consistent with the work of other researchers (Khanzadi, Tadayon *et al*. 2010; Raiess Ghasemi, Parhizkar *et al*. 2010; Hosseini, Hosseini *et al*. 2012; Singh, Bhattacharyya *et al*. 2012).

In another investigation, Li *et al*. (Li, Xiao *et al*. 2004) studied the compressive strength of mortars modified with nano silica. In this study, the results showed an increase in the compressive strength of mortars with the addition of nano silica, at the ages of 7 and 28 days. The enhancement in the 28 days compressive strength was 13.8%, 17%, 26% and 22% with the inclusion of 3%, 5%, 10% and 20% nano silica, respectively. However, Oltulu and Sahin (Oltulu and Sahin 2011) studied the compressive strength of mortars containing 5% SF modified with 0%, 0.5%, 1.25% and 2.5% NS at the ages of 3, 7, 28, 56 and 180. They showed that an increase in the compressive strength with the addition of 0.5% and 1.25% NS, whilst the addition of 2.5% NS reduced the compressive strength.




(a) 3 days (b) 7 days

(c) 14 days (d) 28 days

Fig. 5 Results of compressive strength at various ages

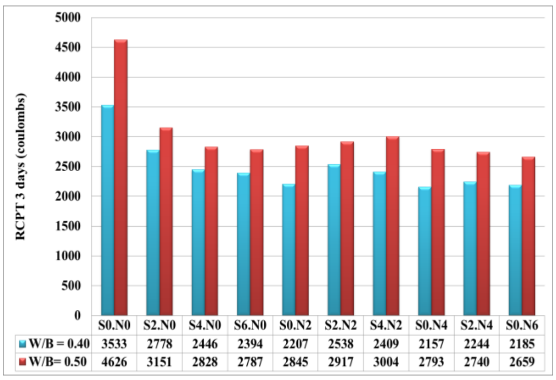
### *4.2 Rapid chloride permeability test (RCPT)*

The average test results for the 3, 7, 14 and 28 days Rapid Chloride Permeability Test (RCPT) of the SCMs are presented in Figs. 6(a) to 6(d). The RCPT result of specimens containing nano silica or silica fume at 28 days varied in the range of 1410 to 1977 coulombs, thus indicated a good chloride durability condition of the SCMs. This is because according to ASTM C1202, the RCPT results, lower than 2000 coulombs generally indicates a low Chloride Ion Penetrability of specimens (ASTM-C1202 2012). The good RCPT attained was mostly due to the improved pore structure of SCMs. Also, the RCPT results of all SCMs at later ages were greater than early ages, which is due to reduced porosity resulting from continued hydration of the cementing materials. In addition, The RCPT results of the SCMs were decreased with lower W/B ratio.

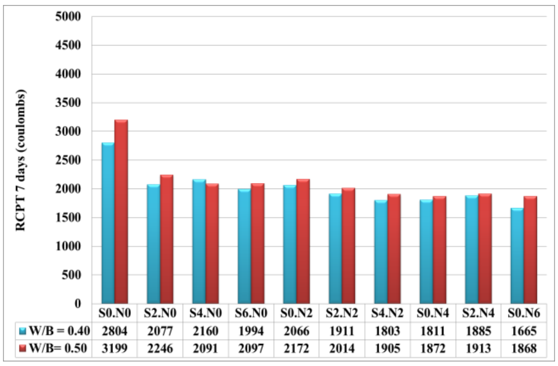
For instance, in the present study, the highest level of RCPT in all ages was achieved for the specimens prepared with the W/B ratio of 0.50. In addition, the presence of nano silica and silica fume decreased the RCPT values, as can be seen in the results. It suggests that the use of silica fume and nano silica improved the quality of SCMs through reduced porosity and densification of their pore structure. As can be seen in SEMs (Figs. 10(a) to 10(f)) the total porosity of SCMs decreased with higher nano silica and silica fume. In addition, it can be seen that the microstructure of specimens was improved in paste matrix and interfacial transition zone. Hence, it was deduced that the increased nano silica content improved the durability of SCMs and produced a greater amount of calcium silicate hydrate (CSH) leading to a lower RCPT value. The similar effect on traditional concretes were noticed in earlier studies (Sadrmomtazi, Fasihi *et al*. ; Raiess Ghasemi, Parhizkar *et al*. 2010). In another study, Said *et al*. (Said, Zeidan *et al*. 2012) show that the passing charge (Coulombs) decreased when the content of NS increased. They show that the penetrability class changed from ‘low’ to ‘very low’ with the addition of nano-silica. Generally, it can be concluded that the decrease in RCPT values is directly related to the reduction in specimens porosity resulting from a greater amount of calcium silicate hydrate.

### *4.3 Water permeability*

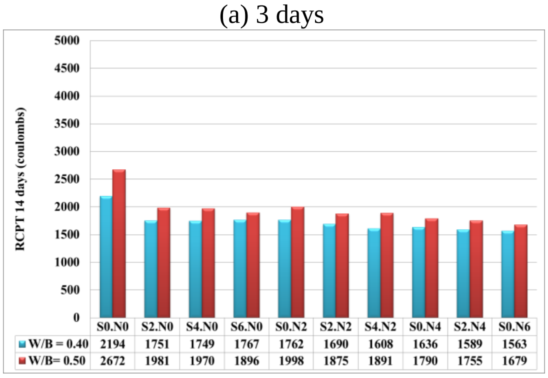
The average test results for the water permeability test of specimens are illustrated in Figs. 7(a) to 7(d). The water permeability ranged from 2 to 20 mm. The lowest level of porosity was obtained for the SCM W40.S0.N6, with the water permeability of 2 mm at 28 days. In contrast, the highest level of porosity was attained for the specimen W50.S0.N0, which provided a water permeability of 20 mm at 28 days. According to Raiess-Ghasemi, *et al*. (Raiess Ghasemi, Parhizkar *et al*. 2010), all specimens are in the low permeability range (penetration depth of less than 30 mm) and the overall test results of water permeability suggesting that the quality of the specimens was suitable. As can be seen from results, the water permeability of the SCMs was increased with higher W/B ratio. A similar effect of the W/B ratio on porosity was observed by other researchers in the case of traditional concretes (Lydon 1995; Roy 1996) Furthermore, the water permeability of the SCMs



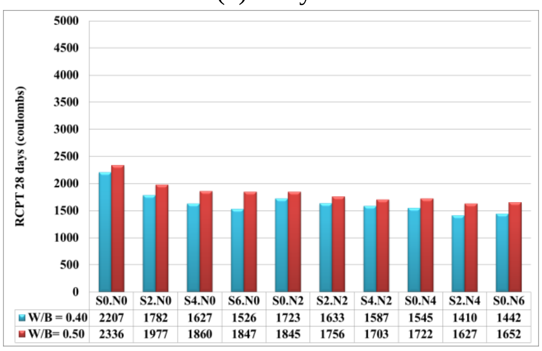

(a) 3 days




(b) 7 days

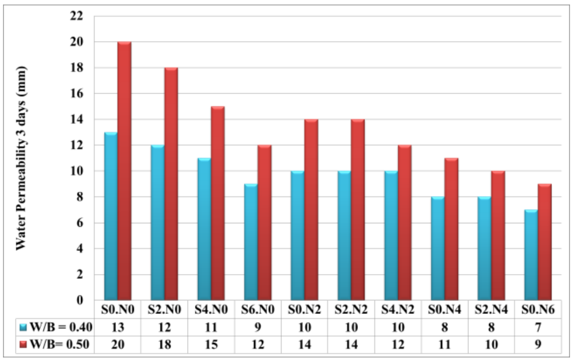



(c) 14 days

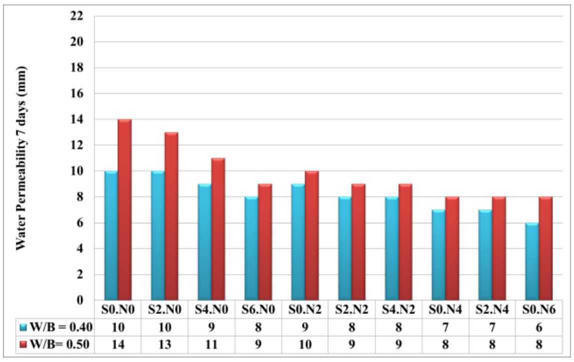



(d) 28 days

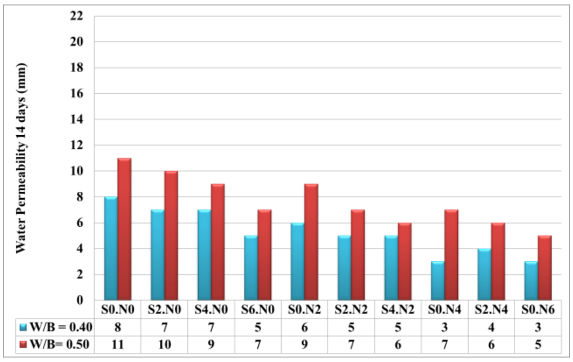
Fig. 6 Results of RCPT at various ages



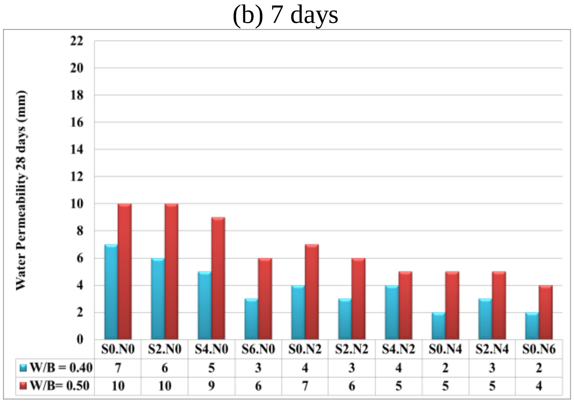

(a) 3 days




(b) 7 days




(c) 14 days



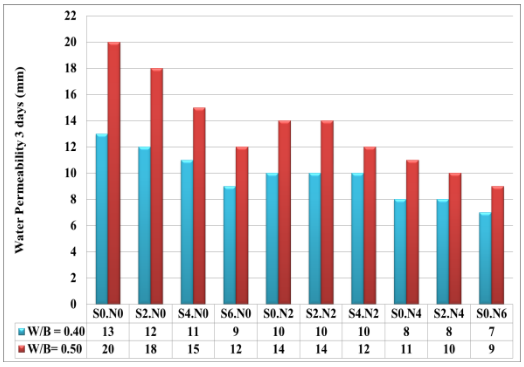

(d) 28 days

Fig. 7 Results of water permeability at various ages

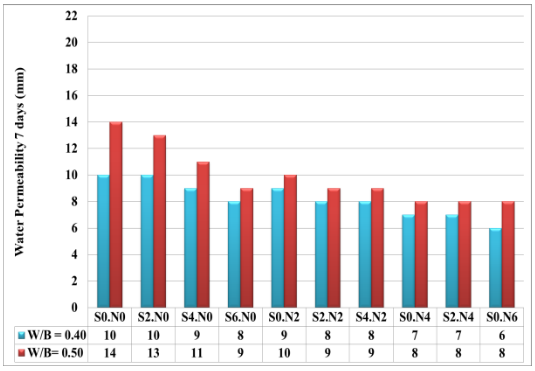
was decreased with greater pozzolanic content, as evident from results. The results showed 55% and 40% approximate reduction with the addition of 6% nano silica and silica fume colloidal and powder NS, at early age of 3 days, respectively. Therefore, it was comprehended that the physical and chemical effects of nano silica and silica fume modified the open channels in the cement paste matrix leading to a discontinuous pore structure with reduced total porosity. Indeed, the presence of nano silica contributes to produce a dense pore structure in SCMs by decreasing the amount and average size of the pores. Similar research was stated by Quercia *et al*. (Quercia, Spiesz *et al*. 2014). They show that the addition of 3.8% nano-silica in concrete decrease the penetration of water under pressure of 0.5 MPa. The results showed 88.46% reduction in the penetration depth of water under pressure with the addition of either colloidal or powder NS. In addition, Raiess Ghasemi, *et al*. (Raiess Ghasemi, Parhizkar *et al*. 2010) show that all mixtures that contain nano silica and/or silica fume, had lower permeability at 91 days, in comparison to the normal concrete.

### *4.4 Capillary water absorption*

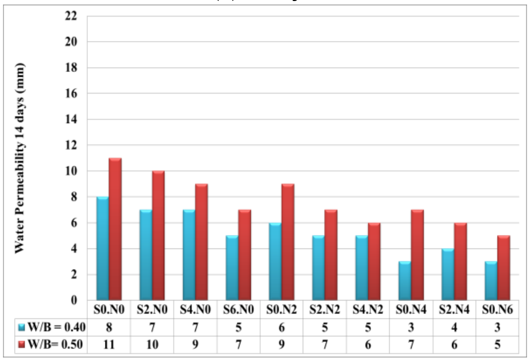
The average test results for the capillary water absorption of the SCMs are illustrated in Figs. 8(a) to 8(d). The lower capillary water absorption was obtained at 28 days for all specimens. Nevertheless, at this age, the capillary water absorption (varied from 0.21% to 0.38%), is very low and could not be a good criterion for evaluating. According to authors' findings (Ramezanianpour, Samadian *et al*. 2012), it can be said that the capillary water absorption of specimens less than 1



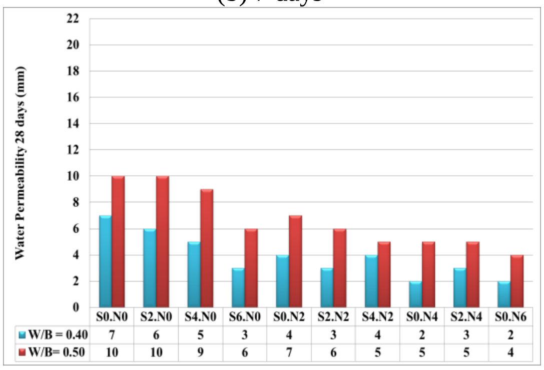

(a) 3 days




(b) 7 days

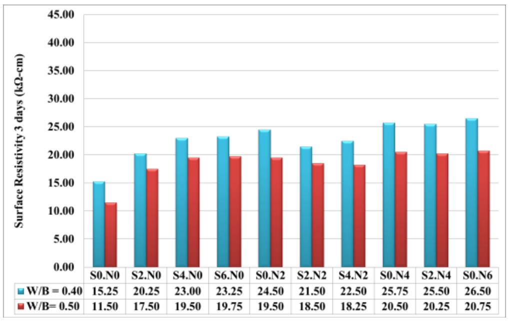



(c) 14 days

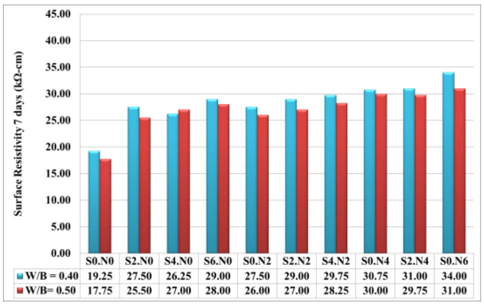



(d) 28 days

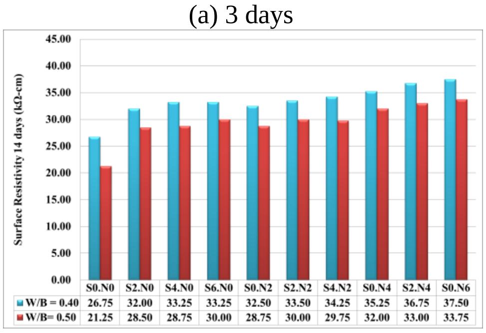
Fig. 8 Results of water permeability at various ages



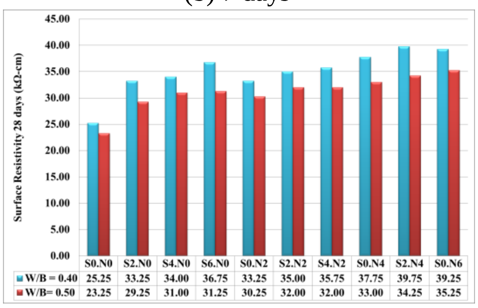

(a) 3 days




(b) 7 days

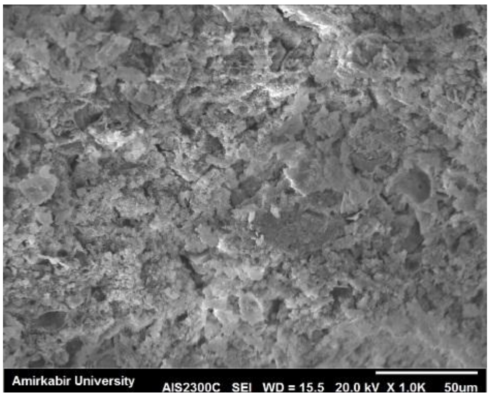



(c) 14 days

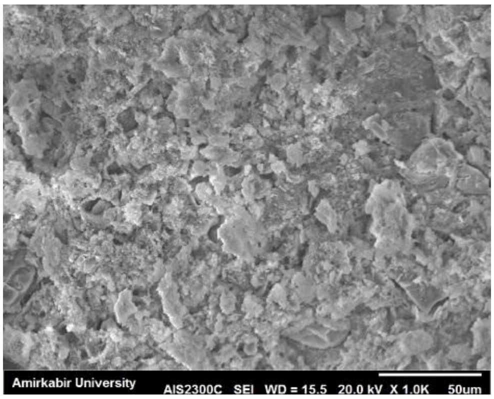



(d) 28 days

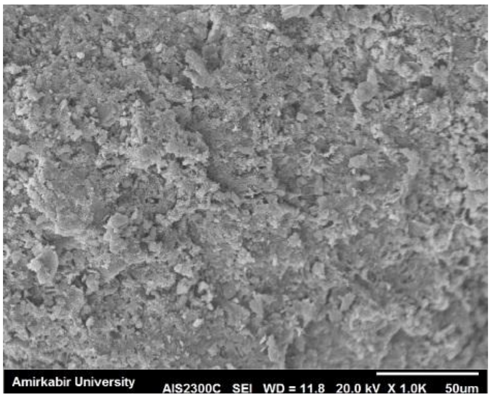
Fig. 9 Results of surface electrical resistivity at various ages



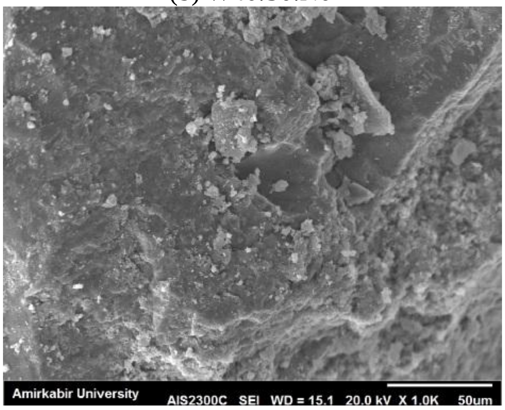

(a) W50.S0.N0



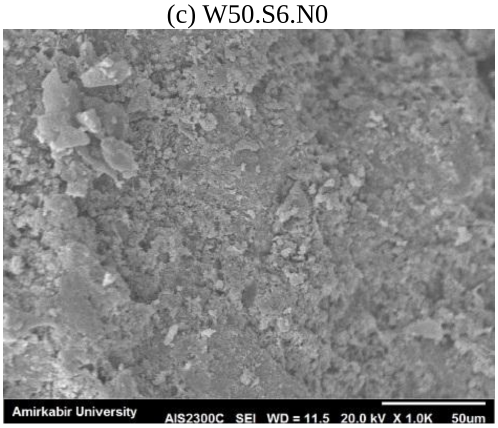

(b) W40.S0.N0



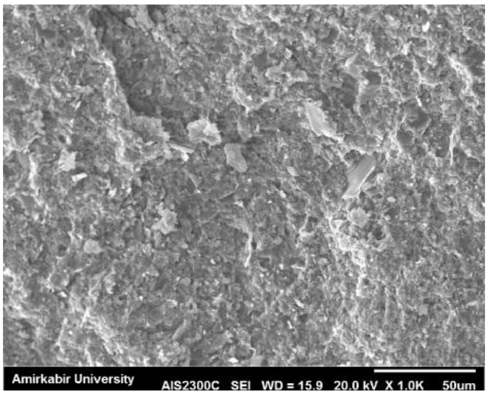

(c) W50.S6.N0




(d) W40.S6.N0




(e) W50.S0.N6




(f) W40.S0.N6

Fig. 10 SEM photograph of SCMs at age of 28 days

kg/m2/hr0.5 is low. As can be seen in SEMs Figs. 10(a) to 10(f) at the age of 28 days, most of the pores are discontinuous and thus the flow channels for the water movement are reduced. In addition, generally it seems that specimens contain silica fume or nano silica provided lower capillary water absorption than plain specimens. In the absence of nano silica and silica fume, the highest level of capillary water absorption was obtained; conversely, the lowest level of capillary water absorption was achieved for the SCMs produced with 6% nano silica. For instance, the lowest level of capillary water absorption at the age of 3 days, was obtained for the specimens W40.S0.N6, which provided 0.27 kg/m2/hr0.5 capillary water absorption. In contrast, the highest level of capillary water absorption was found for W50.S0.N0. Similar results were reported by Nazari and Riahi, Givi *et al*. (Naji Givi, Abdul Rashid *et al*. 2011; Nazari and Riahi 2011). Furthermore, Jalal *et al*. (Jalal, Mansouri *et al*. 2012) show that capillary water absorption decrease 58%, 52% and 54% in the samples containing 2% nano silica compared to normal concrete for binder content of 400, 450 and 500 kg/m3, respectively.

In another investigation, Jalal (Jalal 2013) showed that the pozzolanic admixtures specially blend of silica fume and SiO2 nanoparticles have a significant effect on capillary water absorption. The results of Heidari and Tavakoli's work (Heidari and Tavakoli 2013) show that adding 1% nano silica decreases 14.74% of capillary water absorption compared to the control concrete.

#### *4.4.5 Surface electrical resistivity*

Electrical resistivity of concrete specimens represents moving ions in pore solution. Therefore, the relationship between surface electrical resistivity and chloride permeability is reasonable. (Ramezanianpour, Pilvar *et al*. 2011) The average test results of the surface electrical resistivity are presented in Figs. 9(a) to 9(d). The surface resistivity of SCMs varied in the range of 11.5 to 39.25 kΩ-cm. The results show that the surface electrical resistivity of all specimens were higher at the age of 28 days. The resistance of various SCMs at 28 days was about 35% to 102% higher than that at 3 days. This is due to the reduced porosity at the later age. Furthermore, as can be seen from results, the surface electrical resistivity of SCMs was increased with lower W/B ratio. In the other words, due to the densification of the paste microstructure with reduced porosity, the highest level of resistivity was observed at the W/B ratio of 0.40. The presence of nano silica and silica fume increased the surface electrical resistivity of SCMs. Jalal *et al*. (Jalal, Mansouri *et al*. 2012) showed that use of silica fume and nano silica increases 118% to 236% of surface electrical resistivity at 28 days. In another work, Nili *et al*. (Nili, Ehsani *et al*. 2010) concluded that 6% silica fume and 1.5% nano silica as partial replacements of cement, improved electrical resistance.

## 5. Conclusions

The objective of this paper is to investigate the effect of water to binder ratio, binary and ternary blends use of silica fume and nano silica on the compressive strength and chloride permeability of self-consolidating mortars. Based on the obtained results of this study the following conclusions can be drawn:

- Due to improved paste densification resulting from greater hydration products, the compressive strength of SCMs was improved by increasing the curing time and lower W/B ratio. In addition, in the presence of nano silica and silica fume as a consequence of pozzolanic effects compressive strength increased.
- The results show that with the same content of pozzolanic materials, nano silica specimens had a higher compressive strength than silica fume samples. Similar behavior is observed as well as in other durability test. Therefore, it can be concluded, nanoparticles due to high specific areas are more effective in pozzolanic reaction than silica fume.

- Durability tests relating to chloride ingress (Rapid Chloride Permeability Test, Water Permeability, Capillary Water Absorption, and Surface Electrical Resistivity) indicate that nano silica and silica fume improve durability of concrete, significantly. In addition, as the dosage of nano silica and silica fume slightly increased, the chloride permeability in SCMs significantly improved. This phenomenon indicates that adding small dosages of nano silica and silica fume had a noticeable effect on decreasing the conductivity of concrete and refining the pore structure.
- As can be seen in SEMs, due to the densification of the paste microstructure, total porosity of the SCMs was decreased with lower W/B ratio and higher nano silica and silica fume content, and thus it improved mechanical properties and durability of specimens.

## Acknowledgments

The authors wish to acknowledge Iran Elites National Foundation (BMN) and Iran Nanotechnology Initiative Council for their support of the project.

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